Hillslope Variability in Corn Response to Nitrogen Linked to In-Season Soil Moisture Redistribution

John P. Schmidt,* Nan Hong, Adam Dellinger, Doug B. Beegle, and Henry Lin

ABSTRACT

Spatial variability of corn (*Zea mays* L.) yield within a field is often identified as the primary criterion to justify site-specific nitrogen (N) management; yet, observed yield variability may be unrelated to N supply. The objective of this study was to characterize the spatial variability in economic optimum N rate (EONR) for corn. Ten plot locations were selected in 2005 along a 300-m toposequence of a field in central Pennsylvania. At each location, two replications of six N treatments (0, 56, 112, 168, 224, and 280 kg N ha^{-1}) were broadcast applied at planting as NH_4NO_3. Soil water content (0- to 90-cm depth) was recorded approximately weekly at each location between 5 June and 2 September. The quadratic-plateau response was selected as the most appropriate grain yield response function for 9 of 10 locations and for the field-mean response. The EONR ranged from 47 to 188 kg N ha^{-1} among the nine locations, whereas EONR for the mean response was 137 kg N ha^{-1}. At four of nine locations, observed EONR deviated from field-mean EONR by 40 to 50 kg N ha^{-1}. The relationship between EONR and the change in soil profile water content (0–90 cm) between 30 June and 25 July (representing the driest and wettest soil conditions early in the growing season) was the defining relationship in this study (r^2 = 0.92; $P > F < 0.0001$). Successful site-specific N management depends on an evaluation of the spatial variability in EONR and the corresponding causal factors.

Nitrate contamination of groundwater in the northeastern USA and worldwide has become a regulatory and social issue threatening potable water supplies and endangering wildlife habitat. Most N fertilizer in the USA is applied to corn (*Zea mays* L.), and the dominant management practice for corn production in the Northeast is to apply a single rate of N fertilizer over whole fields and even whole farms. Previous research has indicated that N needs for corn vary among fields (e.g., Schmitt and Randall, 1994; Scharf et al., 2005) and within fields (Blackmer and White, 1998; Scharf et al., 2005). Scharf et al. (2005) indicated that the field–median economical optimum N rate (EONR) among 8 site-years ranged from 63 to 208 kg N ha^{-1}, indicating that field-to-field N management was important to improving overall N management. A uniform N application to fields with spatially variable N requirements leads to frequent mismatches between fertilizer N applied and crop N needs. Less-than-adequate N fertilizer represents an economic risk to the producer, whereas N fertilizer applied in excess of crop requirements leads to excess NO_3 in the soil after crop harvest (Roth and Fox, 1990; Mitsch et al., 2001). This post-harvest residual NO_3 is susceptible to loss by leaching to groundwater and transfers to surface waters via subsurface drainage during the fallow season of humid regions, including the Northeast.

Corn yield variability within a field or between fields has been well documented with precision agriculture technologies (i.e., yield maps), and yield ranging from <1.0 Mg ha^{-1} to >12 Mg ha^{-1} within one field during one growing season is common (Taylor et al., 2001). However, yield variability does not automatically translate into variability in EONR (Vanotti and Bundy, 1994), so developing site-specific N fertilizer recommendations should not automatically follow from a variable yield map. Schmidt et al. (2002) illustrated that irrigated corn yield response functions to N fertilizer for several within-field locations were the same (i.e., maximum yield was obtained with the same N rate), although maximum yield for these same locations ranged from 6.4 to 10.6 Mg ha^{-1} during one growing season. In another irrigated corn field from the same study, maximum yield for several within-field locations was obtained with N rates ranging from 56 to 182 kg N ha^{-1}. Fox and Piekielek (1995) indicated that there was no relationship between maximum yield and EONR (r^2 = 0.08) in their evaluation of 57 site-years in Pennsylvania between 1982 and 1994, despite maximum yields ranging from 6.7 to 12.4 Mg ha^{-1} and EONR ranging from 67 to 212 kg N ha^{-1}. Successful site-specific N management for corn depends on determining the spatial distribution of EONR across a field or between fields within the geographic region of a farm.

Field– and sub-field–scale variability in EONR for corn has been documented recently (Mamo et al., 2003; Scharf et al., 2005), but soil characteristics or other causal factors that could be used to develop a spatial EONR map have not been identified. Katsvairo et al. (2003) concluded that site-specific N management in the Northeast requires more spatial information than is provided by a late spring soil NO_3–N test and/or yield maps from previous growing seasons. Field-to-field (within and across years) variability in EONR ranged from 22 to 203 kg N ha^{-1} for a continuous corn rotation at 11 site-years in Pennsylvania (Fox and Piekielek, 1983). In this same study, EONR varied from 0 to 215 kg N ha^{-1} across all site-years, including various crop rotations and histories of manure application. Despite considerable research in Pennsylvania that demonstrates field-to-field (within and across years) variability in EONR (Fox

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Abbreviations: EONR, economic optimum nitrogen rate.

and Piekielek, 1983, 1995), there has been little or no research that explores whether there might be sufficient within-field spatial variability in EONR to justify site-specific N applications in the Northeast USA.

The hillslope is a typical agricultural landscape unit in the Northeast, with potentially EONR-dependent soil characteristic variability, such as soil water content. Previous research has suggested that water availability may affect EONR. For example, Fox and Piekielek (1998) noted that maximum grain yield in corn was linearly related ($r^2 = 0.69$) to July precipitation for 15 yr of results from a N fertilizer rate study at Rock Springs, PA. In another unpublished report, Fox and Piekielek demonstrated that maximum corn yield was linearly related to July rainfall for rainfall less than 9.4 cm, then reached a maximum yield with a linear-plateau relationship ($r^2 = 0.62$) for 20 yr of results from the Rock Springs farm (the latter report presumably includes data from the 1998 publication). Although not presented by Fox and Piekielek (unpublished report, 2001), EONR from their study was also linearly related ($r^2 = 0.5$; $P > F = 0.001$) to July rainfall but did not result in a plateau-limiting response. In this example, July rainfall was a simple indicator of water availability during a period of rapid vegetative growth (usually 8-leaf growth stage to tasseling) and high water demand by corn; however, spatial variability in soil water availability may have provided a better indicator for yield or EONR.

Variability in soil water content along a hillslope is not simply a function of elevation and rainfall, but, as Famiglietti et al. (1998) demonstrated for a hillslope near Austin, TX, surface soil water content (0–5 cm) depends on soil porosity and hydraulic conductivity during wet soil conditions and on relative elevation, aspect, and clay content during dry conditions. Ridolfi et al. (2003) underscored the complexity of soil moisture dynamics along a hillslope by identifying 10 different phenomena that contribute to soil moisture spatial variability. Pachepsky et al. (2001) used topographic features to explain variability in soil water content and suggested that topographic variability had a potential use for interpreting field-scale variability in precision agriculture.

The objective of this study was to characterize the spatial variability in EONR for corn along a 300-m hillslope, considering the impact of soil water availability on EONR and the potential for using this landscape and soil characteristic for site-specific N management in the northeast USA.

MATERIALS AND METHODS

This experiment was conducted in 2005 at the Russell E. Larson Agronomy Research Farm at Rock Springs in central Pennsylvania. The experimental site was chosen along a 300-m long, westerly aspect hillslope in a rolling agriculture landscape. Total relief along the hillslope was 10 m, with slopes ranging from 1.5 to 5.4% (Fig. 1a). A second-order soil survey (USDA-SCS, 1981) and soil cores (1.1-m depth, 5-cm i.d.) at 10 soil water access tube locations (described below) were used to verify that the soils along the hillslope are Hagerstown silt loams (fine, mixed, semiactive, mesic Typic Hapludalfs). This field had not received any manure applications within the past 20 yr, and the previous crop was soybean [*Glycine max* (L.) Merr.]. Corn (var. Pioneer 34D72) was no-till planted on 3 May 2005. Typical production practices were followed (i.e., herbicides and pesticides to control weeds and pests) except for N fertilizer application. Plant population at harvest was 72 750 ha^{-1}.

Ten evenly spaced locations along the hillslope (Fig. 1a) were selected, each 18.3 m long by 27.5 m wide. Distance between locations was 12.2 m. We evaluated the yield response to increasing N fertilizer rates using a randomized complete block design with two blocks at each location. Plots were six rows wide (4.6 m) and 9.1 m long. Nitrogen fertilizer treatments were 0, 56, 112, 168, 224, and 280 kg N ha^{-1} broadcast applied at planting as granular NH_4NO_3.

Before applying N treatments, soil samples were collected for routine soil analyses at Locations 2, 6, and 10, representing the toe slope, mid slope, and head slope positions, respectively (Fig. 1a). Soil samples (0- to 15-, 15- to 30-, and 30- to 60-cm depths) consisted of three subsamples collected with an open-faced bucket auger (5-cm i.d.) and composited for each depth. Analyses were completed at The Pennsylvania State University Agricultural Analytical Service Laboratory, except for inorganic N, which was determined by flow injection analysis of 2 *M* KCl extracts (QuikChem Methods; Lachat Instruments, Loveland, CO). Results are summarized in Table 1. Surface soil pH ranged from 5.3 to 5.7, which represented slightly less-than-optimum to optimum conditions for growing corn. Surface soil Mehlich 3 soil test P (Wolf and Beegle, 1995) was slightly less than optimum (30–50 mg kg^{-1}) at Location 10 (24 mg kg^{-1}) and optimum to slightly greater than optimum at Locations 2 and 6 (46 and 77 mg kg^{-1}, respectively). Mehlich 3 soil test K (Wolf and Beegle, 1995) (0–15 cm) for these soils was slightly less than optimum (100–150 mg kg^{-1}) to slightly greater than optimum (Table 1). Surface soil organic matter content by loss on ignition (Schulte, 1995) was similar among sites, ranging from 24.3 to 28.7 g kg^{-1} for the highest to lowest landscape positions represented with these three locations. Inorganic soil N (0–15 cm) was considerably greater at the lowest landscape position at 66.2 mg kg^{-1}, compared with 14.7 and 12.1 mg kg^{-1} for the higher landscape positions. General soil nutrient characteristics, except for inorganic N, were similar among soils along this toposequence, representing slightly less than to slightly greater than optimum categories, and represented typical growing conditions in central PA.

Daily rainfall was recorded at a weather station located within 1.2 km of the field. The 30-yr average rainfall was obtained for the State College, PA, weather station, which is located within 5 km of the field, and data were retrieved from http://climate.met.psu.edu/data/IA/ (verified 25 Sept. 2006).

Corn grain was harvested from three of the four inside rows with a combine modified for plot work. Corn grain yield was adjusted to a moisture content of 155 g kg^{-1}. We fitted a quadratic, linear-plateau, quadratic-plateau, and exponential function to evaluate yield response to N treatment at each location. We chose these functions based on the literature (Cerrato and Blackmer, 1990; Schmidt et al., 2002) and the observed shapes of the scatterplots of yield versus N treatment. We assessed the goodness-of-fit of these functions based on the significance of an *F* test and the magnitude, randomness, and normality of the model-fit residuals. An ideal model would have the smallest residuals that exhibit a random pattern and are normally distributed with significant treatment effects. The EONR at each location was determined for selected yield response functions using a N fertilizer cost of \$0.66 kg^{-1} (\$0.3 lb^{-1}) and a corn price of \$0.078 kg^{-1} (\$2 bu^{-1}), equating the first derivative of the response equation to the fertilizer/corn price ratio and solving for *X* (Cerrato and Blackmer, 1990).

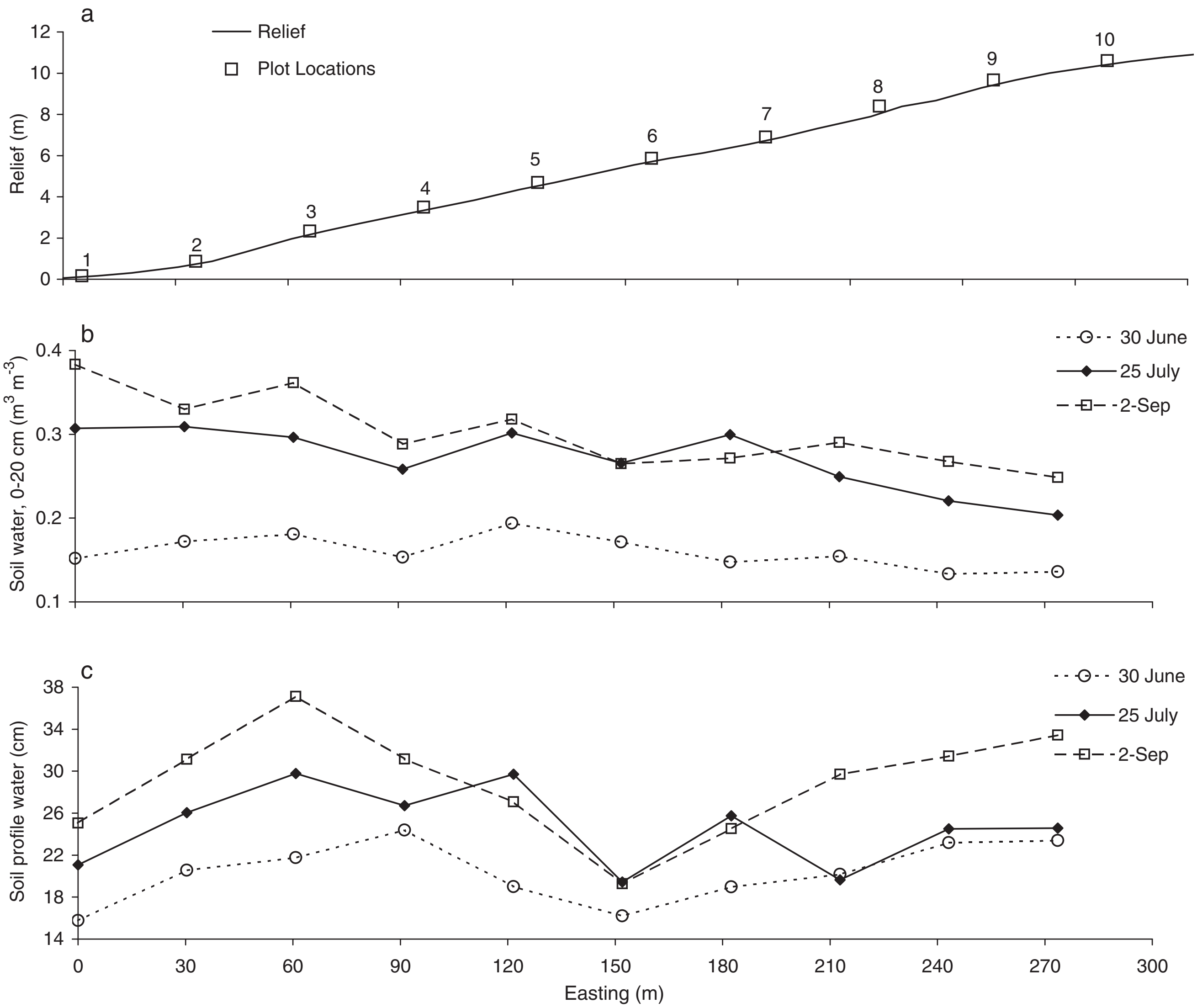

Fig. 1. (a) Local relief along a 300-m toposequence, (b) soil water content (0–20 cm), and (c) soil profile water content (0–90 cm) on 30 June, 25 July, and 2 September. Plot locations are identified numerically on the relief diagram (a). Soil water content was determined 5-m downhill from the plot location.

Nitrogen treatment effects on grain yield were determined with PROC GLM (SAS Institute, 1999). Regression analyses were completed using PROC REG (SAS Institute, 1999) for linear and quadratic functions and PROC NLIN (SAS Institute, 1999) for exponential, linear-plateau and quadratic-plateau functions.

Volumetric soil water content was determined using a factory-calibrated time domain reflectometry moisture meter (TRIME-FM3) with a cylindrical probe (T3 probe) (both from Imko GmbH, Ettlingen, Germany). The TRIME-FM3 provides an effective way to obtain profile soil water content at multiple landscape positions, and the performance of this instrument has been evaluated by Laurent et al. (2005) (RMSE = 0.0662 when compared with neutron probe measurements). Soil water access tubes were installed at Locations 1 through 10 located in the same row (between the first and second plot along the length of the hillslope) adjacent to and immediately

Table 1. Selected soil (0–15 cm depth) characteristics and pre-plant inorganic N (three depths) for three locations along the toposequence.

					Mehlich 3§						Total inorganic N¶		
Location	pH†	Acidity‡	CEC	SOM††	P	K	Ca	Mg	Zn	S	0–15 cm	15–30 cm	30–60 cm
		$cmol_c$ kg^{-1}		g kg^{-1}	mg kg^{-1}						mg kg^{-1}		
2	5.5	4.5	13.6	28.7	46	97	1426	203	2.1	15.0	66.2	13.6	8.3
6	5.3	7.5	12.7	27.1	77	156	836	75	2.5	17.2	14.7	11.0	7.3
10	5.7	3.3	10.8	24.3	24	135	1210	138	1.3	12.5	12.1	9.2	7.5

† 1:1 soil:water pH.
‡ Mehlich Buffer pH.
§ Mehlich 3 extractant and using an inductively coupled plasma spectrophotometer.
¶ NO_3 and NH_4, 2 *M* KCl extract.
†† SOM, soil organic matter.

in front (within 5 m on the downhill side) of each location (Fig. 1). A hydraulic soil probe was used to remove a soil core to 1.1-m depth. One PVC tube (5.0-cm i.d.) was fitted snugly into each hole. Access tubes were not placed in the plots receiving varying N fertilizer rates but were placed in "alley" areas that received a uniform 200 kg N ha^{-1} immediately after planting. We sampled soil water content inside the PVC access tubes at 0- to 20-, 10- to 30-, 30- to 50-, 50- to 70-, and 70- to 90-cm depths at approximately weekly intervals between 5 June and 2 Sept. 2005 and after significant rain events. This period corresponded to approximately the 5-leaf growth stage to grain fill. Equivalent depth of soil water, W_p, was calculated for the top 90 cm of the soil profile using Eq. [1]:

$$W_p = 30\left(\frac{W_{20} + W_{30}}{2}\right) + 20(W_{50} + W_{70} + W_{90}) \quad [1]$$

where W_{20}, W_{30}, W_{50}, W_{70}, and W_{90} are soil water content for the 0- to 20-, 10- to 30-, 30- to 50-, 50- to 70-, and 70- to 90-cm depths, respectively.

RESULTS AND DISCUSSION

Economic Optimum Nitrogen Rate

A significant main effect ($P > F < 0.1$) for N fertilizer was observed at Locations 4 through 9 (Table 2) along this hillslope. Although not significant, the $P > F$ at Locations 1, 2, and 10 was between 0.13 and 0.19, which is suggestive of a significant N treatment effect because two replications at each location do not contribute to a very powerful test for detecting N treatment effect. Location 3 was the only location where yield was not affected by N fertilizer ($P > F = 0.95$). Mean grain yield response to N fertilizer (20 replications) was strongly significant ($P > F < 0.0001$), representing an average response for the entire field.

More interestingly, the type of function that best describes the yield response to N fertilizer treatment and the corresponding EONR at each location were considered. Four different response functions were evaluated for each location: quadratic, linear-plateau, quadratic-plateau, and exponential. These models are commonly used functions for describing corn yield response to N fertilizer (Cerrato and Blackmer, 1990; Schmidt et al., 2002; Scharf et al., 2005).

The quadratic-plateau model provided the smallest residual sum of squares (SS) for 6 of 10 locations (Locations 1, 2, 4, 6, 8, and 9) (Table 2). At Locations 5, 7, and 10, the exponential model provided the smallest residual SS; however, the quadratic-plateau model performed almost as well at these locations, with the residual SS within 5% of those observed for the exponential model. None of the regression models considered at Location 3 was significant. The residual SS for every model at this location was more than twice as great as observed for any response functions at any other location (Table 2). Mean grain yield response to N fertilizer across all 10 locations was best described with the quadratic-plateau function. The quadratic-plateau model is often selected in the literature to describe corn yield response to N fertilizer, especially when summarizing data from multiple fields or years (Derby et al., 2005) or data from strip plots representing the length of a field (Scharf et al., 2005). Selecting the quadratic-plateau model is also consistent with the model selected by Cerrato and Blackmer (1990) in describing corn yield response to N fertilizer at 12 site-years in Iowa. Fox and Piekielek (1995) used the quadratic-plateau model to describe corn yield response to N fertilizer at 57 site-years in Pennsylvania. Because the quadratic-plateau model most often provided the smallest residual SS across all locations, provided the smallest residual SS for the mean grain yield response for this field, and is consistent with examples cited from the literature, this model was selected as the best model from which to proceed in this study in determining EONR. However, because the exponential model provided overall conclusions similar to the quadratic-plateau model and some modelers prefer continuously differentiable response functions, parameter coefficients are also provided for the exponential model.

Parameter coefficients and model statistics for the quadratic-plateau and exponential response functions are provided in Table 3, and the responses are depicted in Fig. 2. The primary difference (besides residual SS) between selecting one of these models in favor of the other is that EONR for the exponential model was generally slightly greater than EONR for the quadratic-response function (Fig. 2), but conclusions based on results from either model were the same.

The quadratic-plateau model was significant ($P > F < 0.007$) at every location except Location 3 (Table 3).

Table 2. Nitrogen treatment main effect (based on ANOVA) and residual sum of squares for four different response models for the relationship between grain yield and increasing N.

			Model residual sum of squares			
Location	N main effect	df	Quadratic	Linear-plateau	Quadratic-plateau	Exponential
	$P > F$					
1	0.1893	5	22.8	21.0	21.0	22.6
2	0.1325	5	12.3	12.3	12.3	14.9
3	0.9489	5	46.1	51.3	52.0	51.7
4	0.0029	5	16.7	9.7	9.7	10.4
5	0.0382	5	18.3	20.2	18.2	17.4
6	0.0049	5	9.3	8.3	8.3	11.6
7	0.0047	5	12.2	10.9	9.7	9.4
8	0.0678	5	17.2	19.8	11.2	11.7
9	0.0352	5	5.9	3.8	3.8	4.1
10	0.1877	5	20.5	21.6	18.7	18.1
Mean	<0.0001	5	299.3	295.5	291.1	295.1

Table 3. Parameter estimates, EONR, and yield at economic optimum N rate (EONR) for quadratic-plateau and exponential models. The response represents grain yield (Mg ha^{-1}) as a function of increasing N (kg ha^{-1}).

Location	Model			Parameter estimates				EONR†	Yield at EONR
	Type	$P > F$	Residual SS	A	B	C	X_0		
								kg N ha^{-1}	Mg ha^{-1}
1	Quadratic-plateau‡	<0.0001	21.0	9.5	0.0335	-10^{-8}	121	121	13.5
2		<0.0001	12.3	7.6	0.0393	-10^{-8}	123	123	12.4
3		0.6214	52.0	10.1	0.2840	−0.00010	36	NA¶	NA
4		0.0001	9.7	6.2	0.1085	−0.00044	94	94	12.5
5		0.0023	18.2	5.7	0.0650	−0.00015	223	188	12.6
6		<0.0001	8.3	6.1	0.0522	-10^{-8}	129	129	12.9
7		<0.0001	9.7	4.4	0.1085	−0.00034	158	147	13.0
8		0.0009	11.2	7.7	0.1045	−0.00051	47	47	11.5
9		0.0003	3.8	8.0	0.0531	−0.00018	96	96	11.5
10		0.0068	18.7	6.2	0.0922	−0.00042	88	88	11.1
Mean		<0.0001	291.1	7.2	0.0619	−0.00018	137	137	12.3
1	Exponential§	0.0299	22.6	14.5	135.1	0.00816	–	188	13.5
2		0.0077	14.9	12.7	62.7	0.01440	–	151	12.1
3		0.8665	51.7	11.1	96.1	0.02460	–	NA	NA
4		0.0001	10.4	12.5	24.8	0.02710	–	112	12.2
5		0.0003	17.4	13.5	46.0	0.01140	–	208	12.8
6		0.0001	11.6	13.8	57.4	0.01030	–	217	13.0
7		<0.0001	9.4	13.6	25.4	0.01500	–	186	13.0
8		0.0068	11.7	11.4	6.3	0.16230	–	27	11.3
9		0.0005	4.1	11.5	48.2	0.02480	–	94	11.2
10		0.0058	18.1	11.3	36.0	0.02250	–	115	10.9
Mean		<0.0001	295.1	12.4	51.8	0.01660	–	140	11.9

† N cost = \$0.66 kg^{-1} (\$0.3 lb^{-1}) and corn price = \$78.64 Mg^{-1} (\$2 bu^{-1}).
‡ If $X < X_0$ then $Y = A + BX + CX^2$; else $Y = A + BX_0 + CX_0^2$.
§ $Y = A(1 - e^{-c(X+b)})$.
¶ NA, The response model was not statistically significant, so EONR and yield at EONR were not determined.

Economic optimum N rate for these nine locations ranged from 47 kg N ha^{-1} at Location 8 to 188 kg N ha^{-1} at Location 5. An EONR was not determined for Location 3 because neither the F test for N effect nor quadratic-plateau regression model were significant (Tables 2 and 3). The EONR for the mean yield response (across all 10 locations) was 137 kg N ha^{-1}. The range in EONR observed in this study is comparable to the range observed by Fox and Piekielek (1995) (67–212 kg N ha^{-1}; mean = 144 kg N ha^{-1}), which represented 57 site-years on fields that had not received manure or been in a forage legume during the previous 2 yr or any legume in the preceding year of the study. The slightly smaller EONR observed in our study could be attributed to soybean as the previously grown crop; otherwise, these results agree with Fox and Piekielek (1995), whose results were obtained from multiple years of studies, of which 43 of the 57 site-years were conducted at the same research farm as the current study.

If the EONR based on the mean yield response (137 kg N ha^{-1}) were selected as the most appropriate N application on this hillslope, 44% of the field would have received N application within 20 kg N ha^{-1} of the observed EONR. The EONR for another 44% of the field deviated from field-mean EONR by 40 to 50 kg N ha^{-1} (Table 3). At Location 8, representing 11% of the field, observed EONR was 90 kg N ha^{-1} less than field-mean EONR. These results are similar to those observed by Scharf et al. (2005), who indicated that EONR for more than 50% of the field deviated from the median EONR by at least 34 kg N ha^{-1}. Variability in EONR along this hillslope implicates the potential for improving N management in this field and in the overall Chesapeake Bay Watershed through site-specific technologies.

The objective of N recommendations developed for corn should be to have producers apply N fertilizer at the EONR, avoiding the economic risk associated with less N and the environmental risks associated with more N. Nitrogen recommendations for corn in many states, which have been designed to be implemented on a field-to-field basis and for large geographic regions, are a linear function of yield (or yield goal). Some examples in this category include Pennsylvania (Beegle, 2004), Colorado (Mortvedt et al., 1996), and Nebraska (Shapiro et al., 2003); whereas some states have developed N recommendations that do not include yield goal (Iowa State University Extension, 1997) or place less emphasis on yield goal (e.g., Minnesota) (Randall et al., 2003). Whether any of these N recommendations designed for large geographic areas can be successfully implemented on a site-specific basis is undetermined; consequently, the type of research presented here is important to improving N recommendations and improving the scientific approach to developing N recommendations based on additional information accessible to producers through new technologies.

Observed grain yield at EONR in this study ranged from 11.1 Mg ha^{-1} at Location 10 (the highest position in this toposequence) to 13.5 Mg ha^{-1} at Location 1 (the toe slope position) (Table 3). The relationship between grain yield at EONR (Mg ha^{-1}) and local relief (m) (omitting Location 3) along this toposequence suggests that local relief could be used as an indicator of yield potential (yield = 13.3–0.167 × local relief; r^2 = 0.59; $P > F$ = 0.02); however, using local relief as an indicator for varying N applications was not supported by the relationship between EONR and local relief. Although greater yield was obtained on lower positions in this

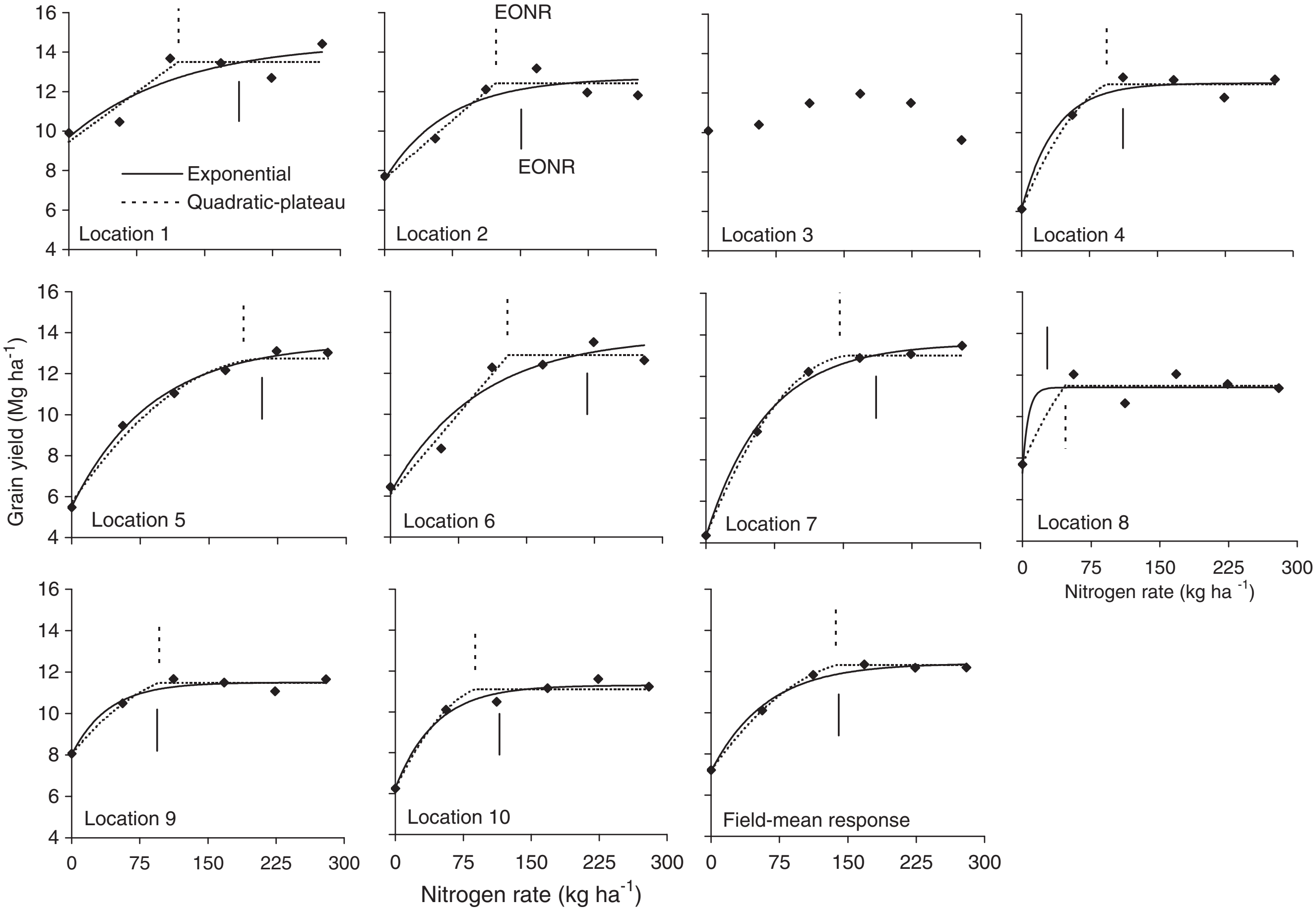

Fig. 2. Grain yield response to N fertilizer for all 10 within-field locations and the field-mean yield response for the entire study area (including Location 3). Parameter estimates for regression equations are provided in Table 3. Vertical lines indicate the economic optimum N rate (EONR) for the corresponding regression equation (solid line for Exponential and dashed line for Quadratic-plateau).

landscape, EONR was unrelated to local relief (r^2 = 0.14; $P > F$ = 0.31). These two relationships seem to suggest that EONR was not related to grain yield, and the relationship between EONR and grain yield at EONR (r^2 = 0.43; $P > F$ = 0.18) (Fig. 3) only marginally supported the concept of making N recommendations based on yield goal. Based on this relationship (Fig. 3), EONR increased from 68 to 141 kg N ha^{-1} as grain yield observed at EONR increased from 11.1 to 13.1 Mg ha^{-1} (Fig. 3). This corresponds to a mean increase of 36.6 kg N Mg^{-1} (2.05 lb N bu^{-1}) between 11.1 and 13.1 Mg ha^{-1}. Although this yield response does not constitute overwhelming evidence in support of N recommendations that are a linear function of yield goal, these results are important when considering the implication for site-specific N management. Should site-specific N recommendations for this field be based on yield goal (i.e., an extension of traditional N recommendations), a spatial map of which can be easily obtained by a producer with a yield monitor?

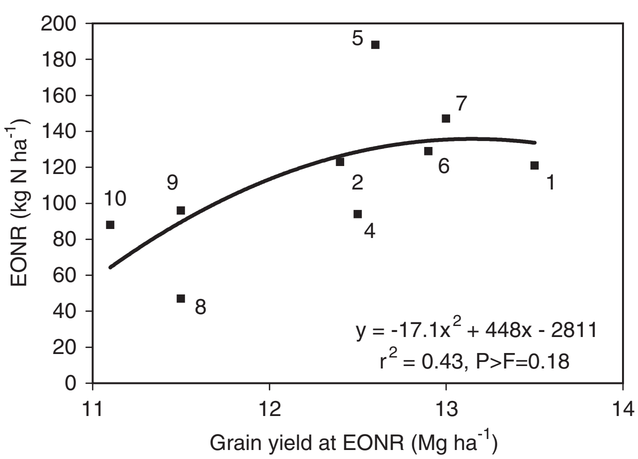

Fig. 3. Economic optimum N rate (EONR) as a function of grain yield at EONR for nine within-field locations (Location 3 omitted).

In-Season Soil Water Content

Soil moisture deficit stress has long been known to reduce grain yield for any crop. The effect is considered self-evident, and the duration and timing of this stress during crop development has practical implication for irrigation management. Stress occurring during the tasseling and silking stages of corn development usually has greater negative impact on yield than stress occurring during the earlier vegetative stages (Denmead and Shaw, 1960; NeSmith and Ritchie, 1992; Çakir, 2004). Fox and Piekielek (1998) observed a linear relationship between July precipitation and maximum corn grain yield ($r^2 = 0.69$) from 15 yr of a N fertilizer study at the same research farm as the current study. Fox and Piekielek (unpublished report, 2001) later demonstrated, with the continuation of the same study, that maximum corn yield increased linearly as July rainfall increased to 9.4 cm; with additional rainfall in excess of 9.4 cm, yield remained constant in a linear-plateau type relationship. Using Fox and Piekielek's results, we determined that EONR was linearly related to July rainfall ($r^2 = 0.5$; $P > F = 0.001$), which can be considered a convenient measure of water availability to the growing crop. Because soil water availability can vary significantly along a hillslope (Famiglietti et al., 1998; Ridolfi et al., 2003) and because year-to-year variability in July rainfall was an indicator of corn grain yield and EONR variability for previous studies at the current research farm, perhaps within-field variability in soil water availability during one growing season directly affects EONR.

Although irrigation was not available to supplement rainfall in this study, soil water content (0–20 cm and 0–90 cm) was slightly greater between late July and mid-August (Fig. 4; coinciding with tasseling to grain fill period of crop development) than earlier in the growing season (e.g., 30 June and 8-leaf stage). Consequently, maximum yield, or grain yield at EONR (11.1–13.5 Mg ha^{-1}) (Table 3), met or exceeded general expectations for this central Pennsylvania production field. The below-normal early season rainfall (Fig. 4) seemed to be masked by the July–August rainfall observed in 2005. The July rainfall (12.4 cm) exceeded the yield-limiting July rainfall (9.4 cm) determined by Fox and Piekielek (unpublished report, 2001), and grain yield observed in 2005 exceeded maximum grain yield (10.4 Mg ha^{-1}) observed by Fox and Piekielek. However, the amount of water available to a growing crop is not simply a function of rainfall, as illustrated by the 10 processes affecting hillslope hydrology that were identified by Ridolfi et al. (2003).

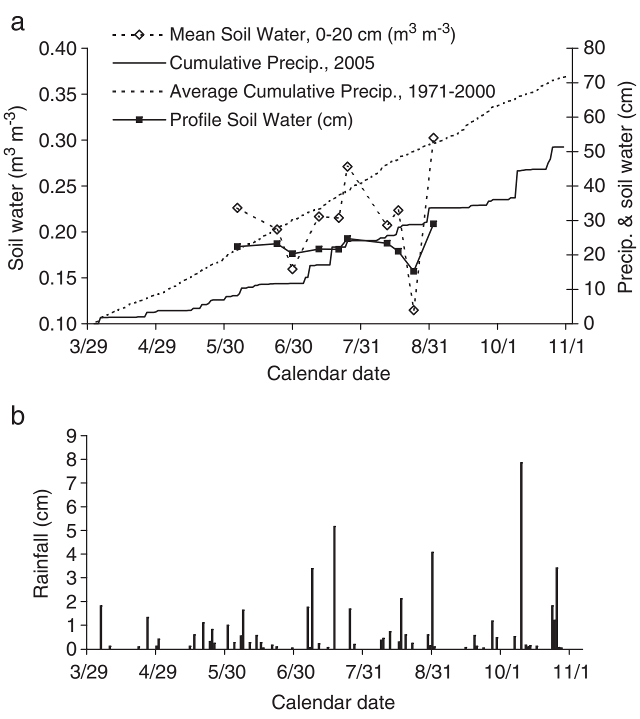

Fig. 4. (a) Cumulative daily precipitation (1 April–31 October) for 2005; the 30-yr average for State College, PA; mean soil water content (0–20 cm); and mean profile water content (0–90 cm) observed for all 10 locations. (b) Daily precipitation at the study site.

On 30 June, mean soil water content in the top 20 cm of soil (0.16 m^3 m^{-3}) was the lowest observed early during the 2005 growing season (before 24 August) (Fig. 4a). Between 30 June and 25 July, rainfall accumulation (0.49 cm d^{-1}) was slightly more than the 30-yr average (0.35 cm d^{-1}) (Fig. 4a). As a result of the increased rainfall during early July, mean soil water content in the top 20 cm increased to 0.27 m^3 m^{-3} on 25 July, and mean soil water content in the 0- to 90-cm profile increased 4.4 cm (Fig. 4a). The mean increase in profile soil water content was slightly more than one third of the total rainfall (12.2 cm) during this period. However, the increase in profile soil water content between 30 June and 25 July was quite variable along this hillslope, ranging from −0.54 cm at Location 8 to 10.7 cm at Location 5 (Fig. 1c). These differences in the change in profile soil water content between 30 June and 25 July reflect differences in soil and landscape characteristics that affect water redistribution within this landscape.

Soil water content along this hillslope was less variable on 30 June, corresponding to dry soil conditions, than on 25 July and 2 September, corresponding to wetter soil conditions (Fig. 1b and 1c). Famiglietti et al. (1998) observed similar behavior in water variability in the surface soil (0–5 cm) along a 200-m hillslope near Austin, TX, attributing spatial heterogeneity in soil moisture under wet conditions to soil variability, and noted that joint influences of topography and soil properties contributing to more similar soil water content along the hillslope under drier conditions. Although we have not conducted a detailed analysis to describe the processes affecting water redistribution for this hillslope, the changes observed in soil water content (Fig. 1b and 1c) are suggestive of processes described by Famiglietti et al. (1998).

Perhaps less than 100% of rainfall in early July infiltrates at Location 8, whereas infiltration may equal rainfall at Location 5 and/or the soil at Location 5 is a beneficiary of subsurface redistribution of rainfall resulting in a change in profile soil water content almost equal to rainfall, despite evapotranspiration by a growing corn crop. Greater available water in the 0- to 90-cm soil profile during a growing season with less-than-normal precipitation translated to greater grain yield at EONR (Fig. 5). As the net change in soil profile water content between 30 June and 25 July increased from −0.5 cm to 7.3 cm, grain yield increased from slightly more than 11 Mg ha^{-1} to slightly more than 13 Mg ha^{-1} ($r^2 = 0.66$; $P > F = 0.04$) (Fig. 5). Relationships between grain yield at EONR and the change in soil profile water content (Fig. 5) and between EONR and grain yield at EONR (Fig. 3) suggest that there might be a significant

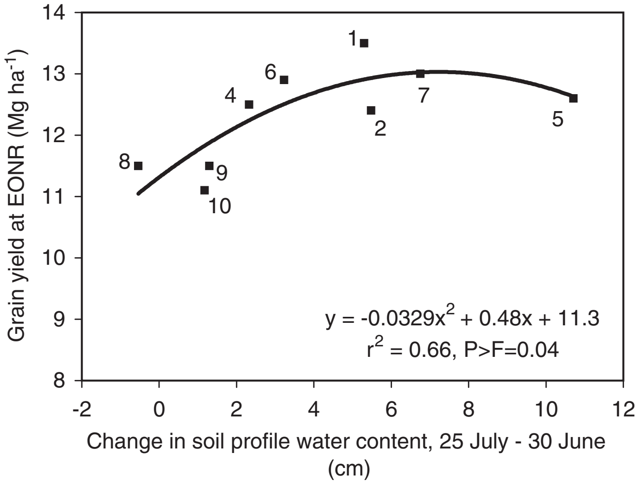

Fig. 5. Grain yield at economic optimum N rate (EONR) as a function of the change (25 July–30 June) in soil profile water content (0–90 cm) between 30 June and 25 July.

relationship between EONR and the change in soil water profile content.

Economic optimum N rate increased linearly with increasing change in soil profile water content between 30 June and 25 July ($r^2 = 0.92$; $P > F < 0.0001$) (Fig. 6). At locations where soil profile water content increased the most between 30 June and 25 July, reflecting soil physical conditions and/or a landscape position that favorably accumulates water during a relatively dry growing season, greater N fertilizer was required to reach maximum yield. Because this is only a correlative relationship, no specific causal effect can be attributed to the soil profile water content increase between 30 June and 25 July, but this relationship demonstrates that there are soil and/or landscape characteristics that can be identified (or the impact of which can be captured) that provide a much better indicator of N requirement for corn as compared with yield (Fig. 3) or yield potential.

Although EONR should be the primary determinant in developing N recommendations, fluctuation in the fertilizer/corn ratio may affect the outcome of the relationship described in Fig. 3. Nitrogen rate corresponding to maximum yield is provided in Table 3 (as X_0), and X_0 also increased linearly with an increase in the change in soil profile water content between 30 June and 25 July ($r^2 = 0.93$; $P > F < 0.0001$), suggesting that the fertilizer/corn ratio may have little impact on this relationship.

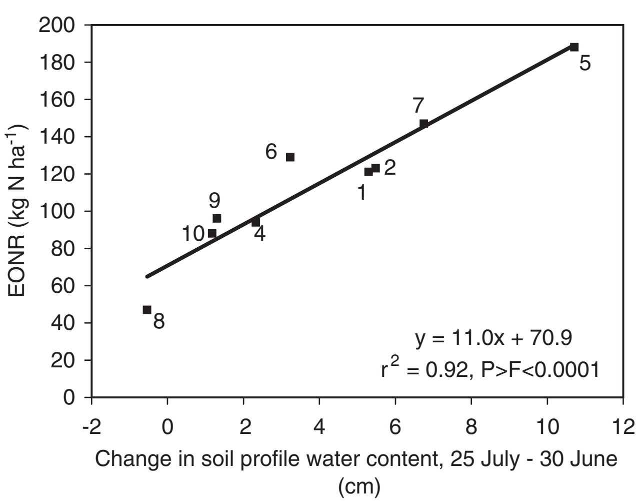

Fig. 6. Economic optimum N rate (EONR) as a function of the change (25 July–30 June) in soil profile water content (0–90 cm) between 30 June and 25 July.

These results underscore the importance in understanding the spatial variability in EONR, not simply understanding or capturing yield variability. Although there was evidence of a relationship between EONR and grain yield at EONR (Fig. 3) and a significant relationship between grain yield at EONR and the change in soil profile water content (Fig. 5), the defining relationship seems to be the one between EONR and the change in soil profile water content between 30 June and 25 July (Fig. 6). The driest part of the growing season with respect to soil water content (30 June, Fig. 4a) coincided with the period of rapid vegetative growth in corn and a very high water demand by the crop. The quite variable EONR among these 10 within-field locations (Table 3) identifies an opportunity for site-specific N management in the Northeast USA. If, as the results from this study and previous studies at this same research farm suggest, soil water availability during July is an important indicator of EONR, the practical question is: How will a producer obtain this information? Adequate soil characteristic data might be obtained through soil electrical conductivity maps and selected soil sampling and analyses to verify the electrical conductivity map. Fine-resolution topographic maps are becoming increasingly available, and Schmidt et al. (2003) demonstrated how a topographic map might be obtained with repeated passes with a typical agricultural global positioning receiver. Distributed hydrologic models could then be used to estimate soil moisture variability along a hillslope (Famiglietti et al., 1998). Although these various tools are not available to producers for site-specific N management, future research should emphasize an evaluation of site-specific EONR and provide the direction for the development of the appropriate producer tools. Development of appropriate response models will not only depend on the correlative relationships observed in this study, but also on an improved understanding of the causal relationships between soil physical and/or landscape characteristics and EONR. Eliciting these types of causal relationships with EONR, which may be unique to individual fields or perhaps to a geographic region, is the challenge for site-specific N management research.

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